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A METHOD FOR ESTIMATING WIND-WAVE GROWTH AND DECAY IN SHALLOW W--ETC(U)

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A Method for Estimating Wind-Wave Growth and Decay in Shallow Water With High Values of Bottom Friction

by

Frederick E. Camfield

COASTAL ENGINEERING TECHNICAL AID NO. 77-6
OCTOBER 1977

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This report presents an approximate method for estimating wind-wave growth and decay over flooded areas where there is a major effect from bottom friction because of dense vegetation.

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PREFACE

This report describes a method for estimating wind-wave growth and decay over flooded areas where there is a major effect from bottom friction because of dense vegetation. The report was initiated in response to a request from the U.S. Army Engineer Division, Lower Mississippi Valley, New Orleans District, at the Division's 14 September 1976 Research and Development Workshop, indicating a need for technical guidelines for predicting wind-wave generation over flooded coastal areas. The work was conducted under the coastal construction program of the U.S. Army Coastal Engineering Research Center (CERC).

These technical guidelines are an extension of the procedures given in the Shore Protection Manual (SPM) (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1975). The design curves in the SPM are limited to waves passing over a sandy bottom. The guidelines presented in this report are discussed at greater length in CERC Technical Paper No. 77-12 (Camfield, 1977).

This report was prepared by Dr. Frederick E. Camfield, Hydraulic Engineer, under the general supervision of R.A. Jachowski, Chief, Coastal Design Criteria Branch.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

JOHN H. COUSINS
Colonel, Corps of Engineers
Commander and Director

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CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.8532	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton-meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.1745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1]To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$.
To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

SYMBOLS AND DEFINITIONS

d	water depth
d_i	water depth at seaward or beginning edge of segment
F	fetch length
F_a	adjusted fetch length for distance across a segment in the direction of wave motion
F_e	equivalent fetch length for the initial wave at the seaward or beginning edge of the segment
f_f	bottom-friction factor (Darcy-Weisbach friction factor)
f_{fi}	bottom-friction factor at seaward or beginning edge of the segment
G_i	fractional growth factor of equivalent initial wave
g	gravitational acceleration
H	wave height
H_D	decayed wave height at the end of the fetch
H_e	equivalent wave height at the end of the fetch
H_f	wave height at end of fetch
H_i	wave height at seaward or beginning edge of the segment
H_{ie}	equivalent initial wave height
H_m	maximum stable wave height
H_{sm}	maximum significant wave height which would be generated for a given windspeed and water depth
K_f	decay factor
$K_{f.01}$	decay factor when the bottom-friction factor, $f_f = 0.01$
K_{fa}	decay factor when the bottom-friction factor, f_f, has a value different than 0.01
K_s	shoaling coefficient
L	wavelength

SYMBOLS AND DEFINITIONS--Continued

R_i	fractional reduction of initial wave at the seaward edge of the segment, as compared to the maximum stable wave height
T	wave period
U	windspeed
x	distance in the direction of wave motion
α	factor for reducing fetch length to the adjusted length
α_r	factor for increasing fetch length to the adjusted length = $1/\alpha$
Δ	incremental change
Δx	actual distance across a segment in the direction of wave travel

A METHOD FOR ESTIMATING WIND-WAVE GROWTH AND DECAY IN SHALLOW WATER WITH HIGH VALUES OF BOTTOM FRICTION

by
Frederick E. Camfield

I. INTRODUCTION

An important factor in the planning and design of works to protect upland property during periods of storm surge involves the prediction of the wave height and period that will prevail at and seaward of the protective works (i.e., levee, dike, seawall, etc.) for the selected design storm. Although improvements are needed, guidelines are available for prediction of the water levels in upland areas that will result from storm surge; however, no guidelines are presently available for computing the wave attenuation for conditions when a storm-generated wave travels a distance across a shallow flooded area where the bottom characteristics include vegetation which causes a moderate to high frictional stress. Therefore, it is necessary to estimate the heights and periods of waves which have traveled across a shallow flooded area. At times the initial heights and periods of the waves may increase; i.e., when the wind stress exceeds the frictional stress of the ground and vegetation underlying the shallow water. The initial wave heights may decay at other times when the frictional stress exceeds the wind stress.

This report presents a *preliminary* (approximate) method for estimating the growth or decay of waves traveling through shallow water over areas with a high frictional resistance from vegetation. The method is based on previously developed equations for wave growth over areas with low bottom friction given in the Shore Protection Manual (SPM) (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1975)[1], and an equation for the decay of gravity waves over areas with a constant water depth and high bottom friction. The method uses existing shallow-water wave forecasting curves by adjusting fetch lengths to account for higher bottom friction. Simplifying assumptions are used. The water depth is assumed to have only gradual variations, and the frictional resistance is treated as bottom friction. The method presented has not been verified in the field and may not be applicable to other problems relating frictional resistance to wave development.

Only limited data are available at this time on the effects of high values of bottom friction on wind waves. Friction factors are estimated by comparing vegetation to similar conditions in river channels and on flood plains. The effect of the vegetation on wind stress, the possible effects of motion of the vegetation, and the dense vegetation effects near the water surface which will damp out short-period waves much faster than long-period waves are *not considered*. The results obtained are considered

[1]U.S. ARMY, CORPS OF ENGINEERS, COASTAL ENGINEERING RESEARCH CENTER, *Shore Protection Manual*, 2d ed., Vols. I, II, and III, Stock No. 008-022-00077-1, U.S. Government Printing Office, Washington, D.C., 1975.

conservative; i.e., the predicted wave heights are expected to be slightly higher than the wave heights which actually occur.

Wave prediction curves for waves passing through shallow water where the bottom friction, $f_f = 0.01$, are shown in Figures 1 and 2. For any given windspeed, U, and water depth, d, there is a maximum (depth-limited) significant wave height, H_{gm}, which would be generated (long dashline in Fig. 1).

Where H_i, the initial wave height at the seaward or beginning edge of the fetch, is less than H_{gm}, the wave would increase in height. Where the bottom friction, $f_f > 0.01$, the wave would not become as high as a wave traveling over a bottom where $f_f = 0.01$, with the segment fetch distance, Δx, being the same in both cases. Therefore, an adjusted fetch, $F_a < \Delta x$, would be used to describe the wave, using Figures 1 and 2 which were developed for the case of $f_f = 0.01$. Except for specific water depths, Figures 3 to 12 (after SPM) show the same results as Figures 1 and 2.

Where $H_i > H_{gm}$, the wave would decay. As a value of $f_f > 0.01$ would cause a wave to decay a greater amount than if it were traveling over a bottom where $f_f = 0.01$, an adjusted fetch, $F_a > \Delta x$, would be used in this case.

The details of this method are discussed by Camfield (1977)[2].

II. FETCH ADJUSTMENT

The fetch should initially be divided into segments so that (a)

$$\Delta d < 0.25\ d_i \tag{1}$$

where Δd is the change in depth over the distance across the segment in the direction of wave motion, and d_i is the depth at the seaward or beginning edge of the segment; (b)

$$\Delta f_f < 0.25\ f_{fi} \tag{2}$$

where Δf_f is the change in the bottom-friction factor over the segment distance, and f_{fi} is the bottom-friction factor at the beginning edge of the segment; and (c) after computation of the wave height at the end of the fetch,

$$\Delta H < 0.5\ H_i \tag{3}$$

where ΔH is the change in the wave height over the segment distance and H_i is the wave height at the beginning edge of the segment. Each segment of the fetch can then be considered separately using the method indicated.

[2]CAMFIELD, F.E., "Wind-Wave Propagation over Flooded, Vegetated Land," TP 77-12, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., Oct. 1977.

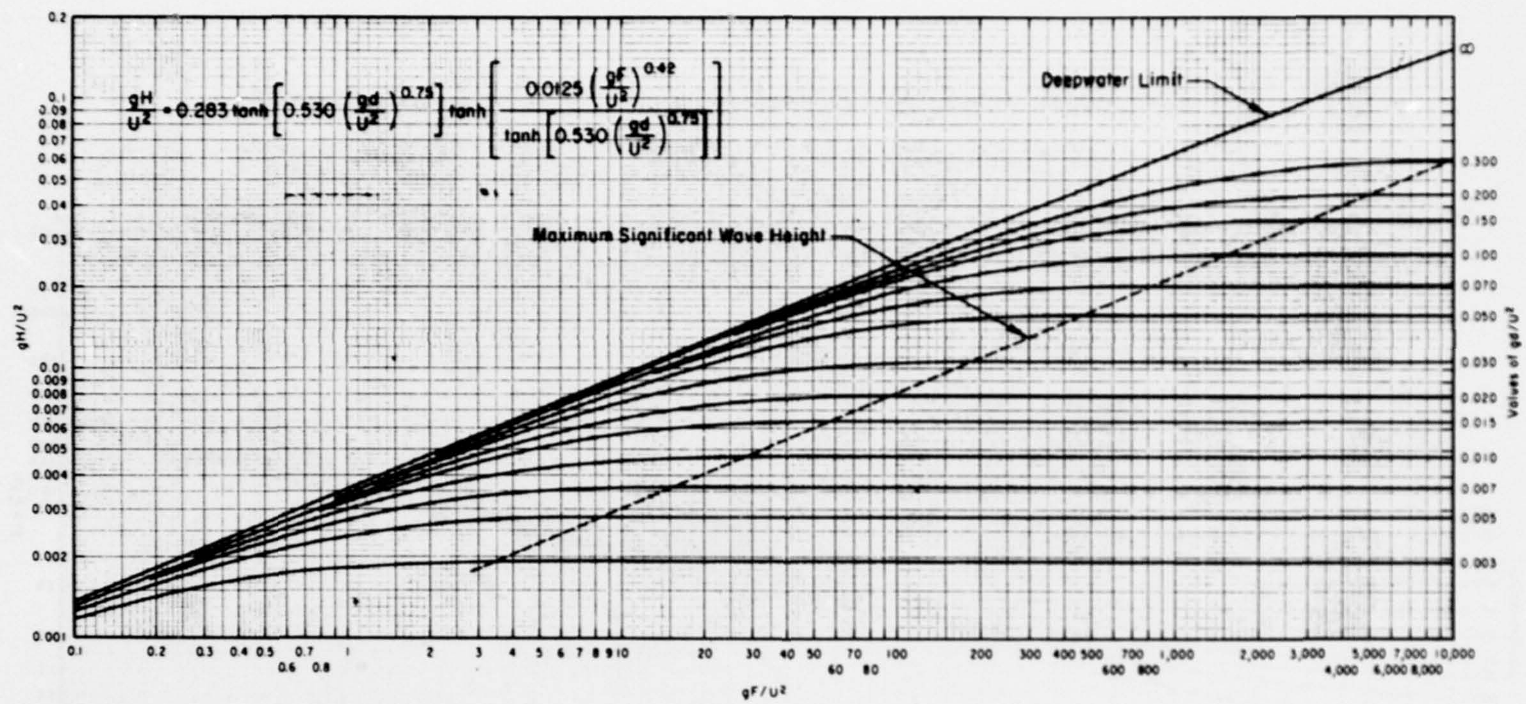

Figure 1. Forecasting curves for wave height, water depths constant.

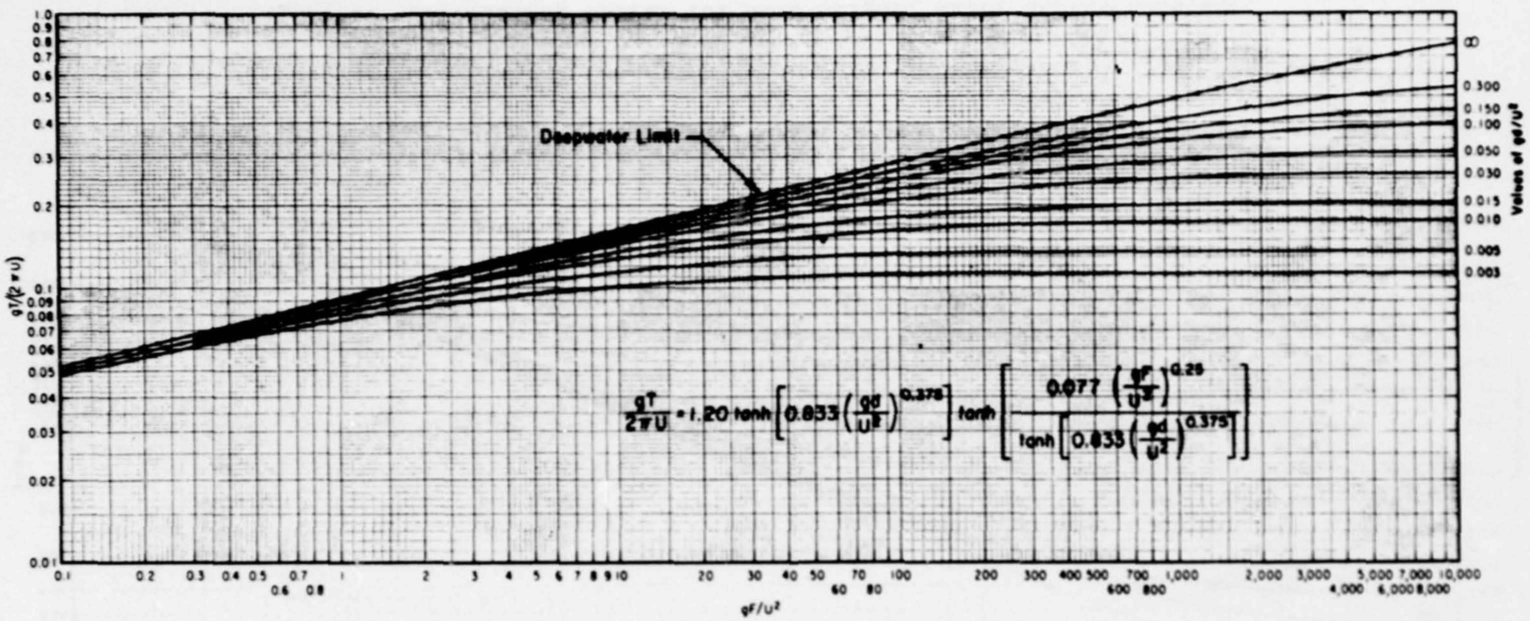

Figure 2. Forecasting curves for wave period, water depths constant.

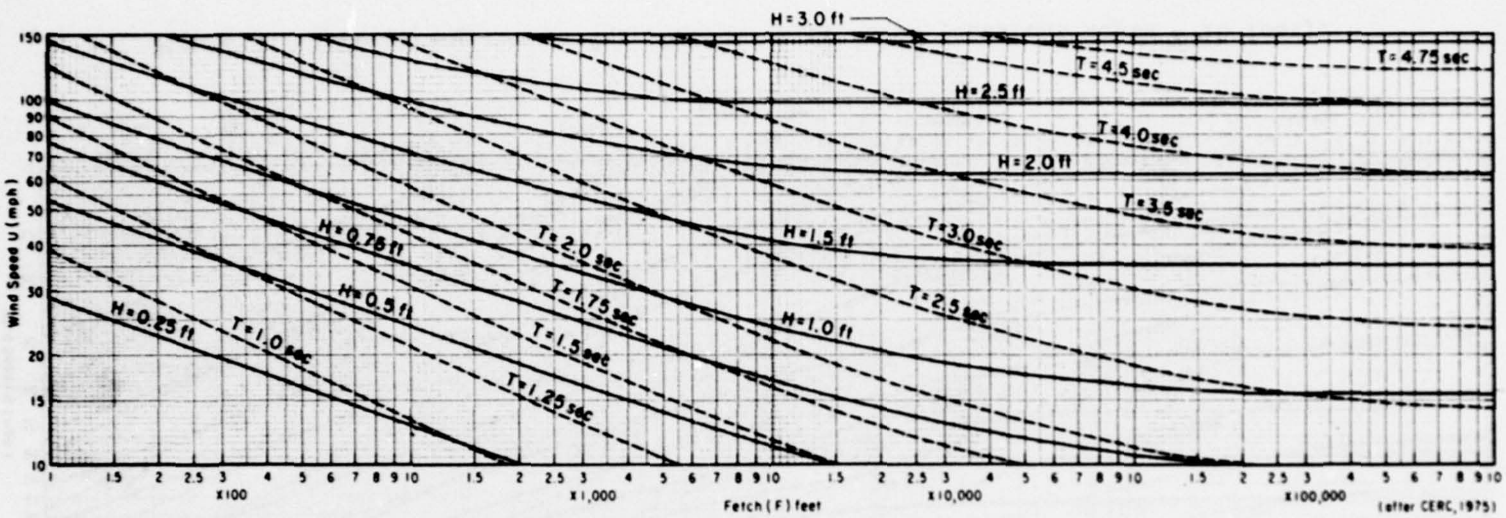

Figure 3. Forecasting curves for shallow-water waves (constant depth = 5 feet).

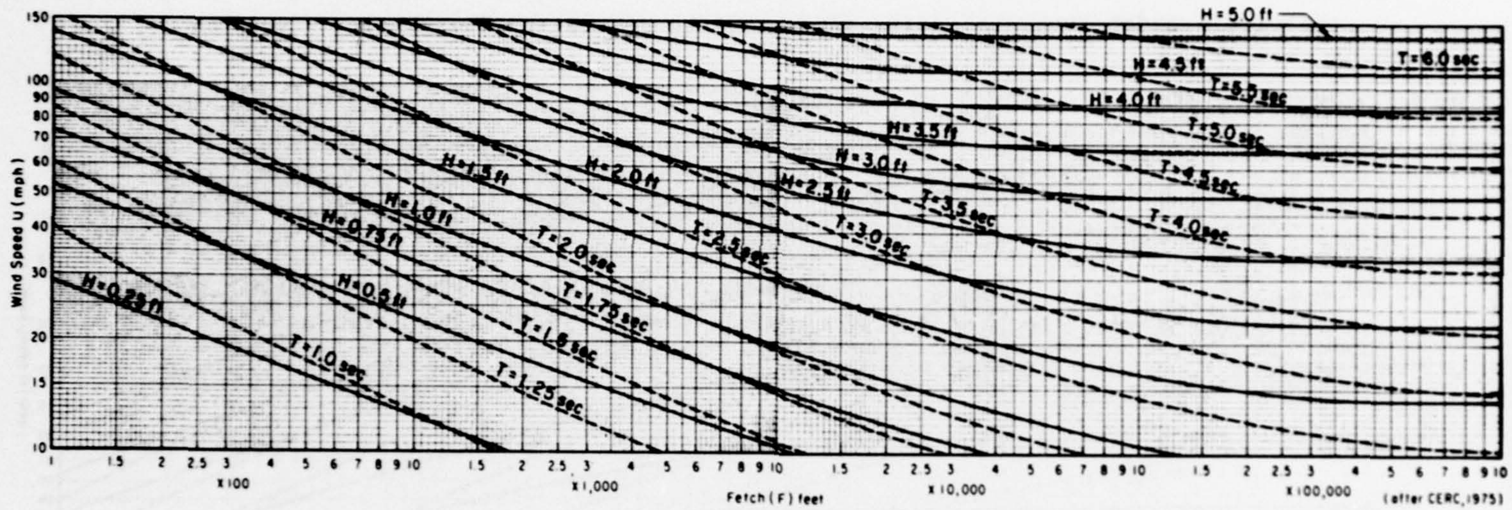

Figure 4. Forecasting curves for shallow-water waves (constant depth = 10 feet).

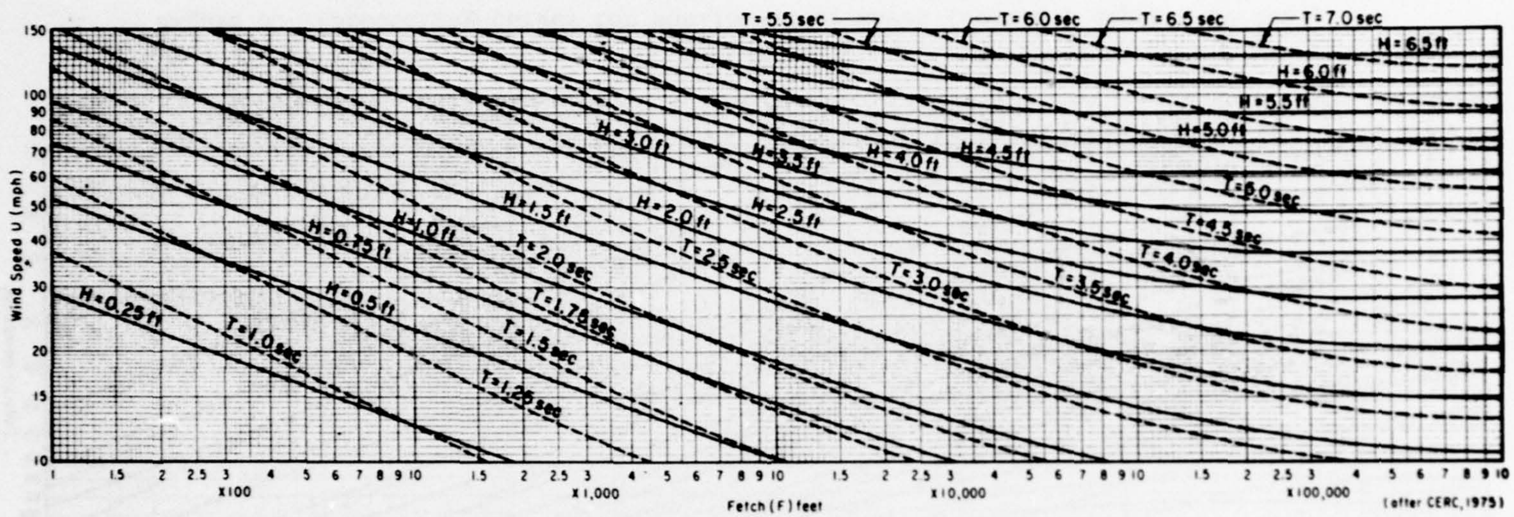

Figure 5. Forecasting curves for shallow-water waves (constant depth = 15 feet).

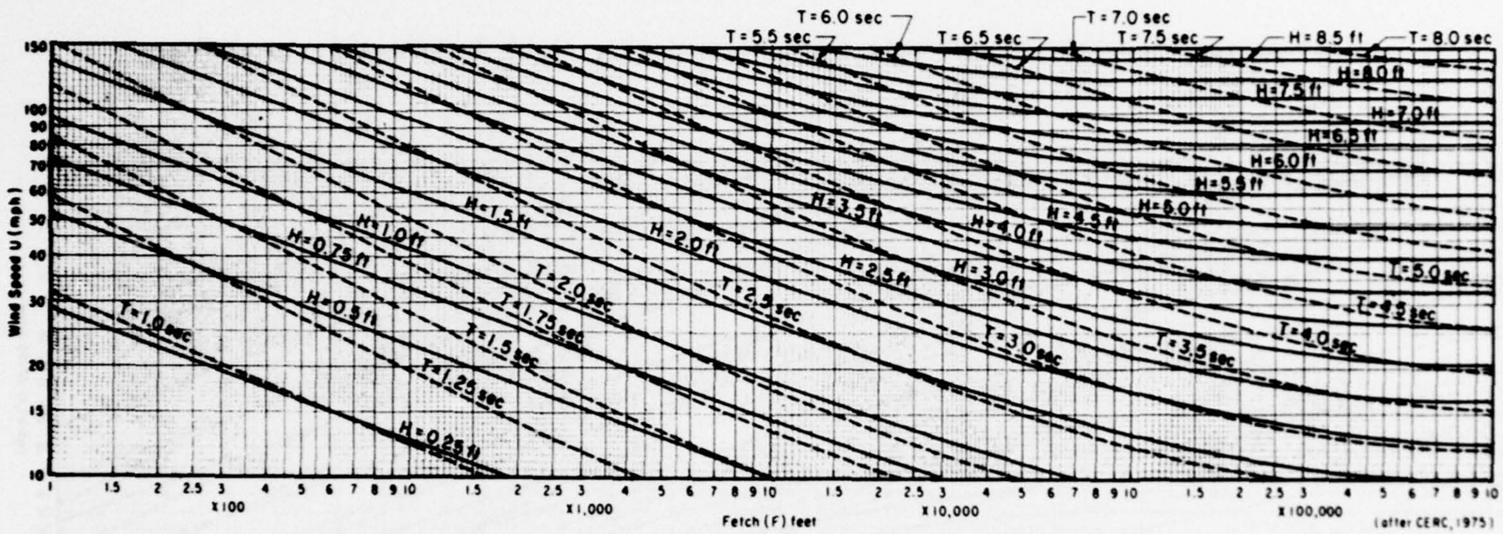

Figure 6. Forecasting curves for shallow-water waves (constant depth = 20 feet).

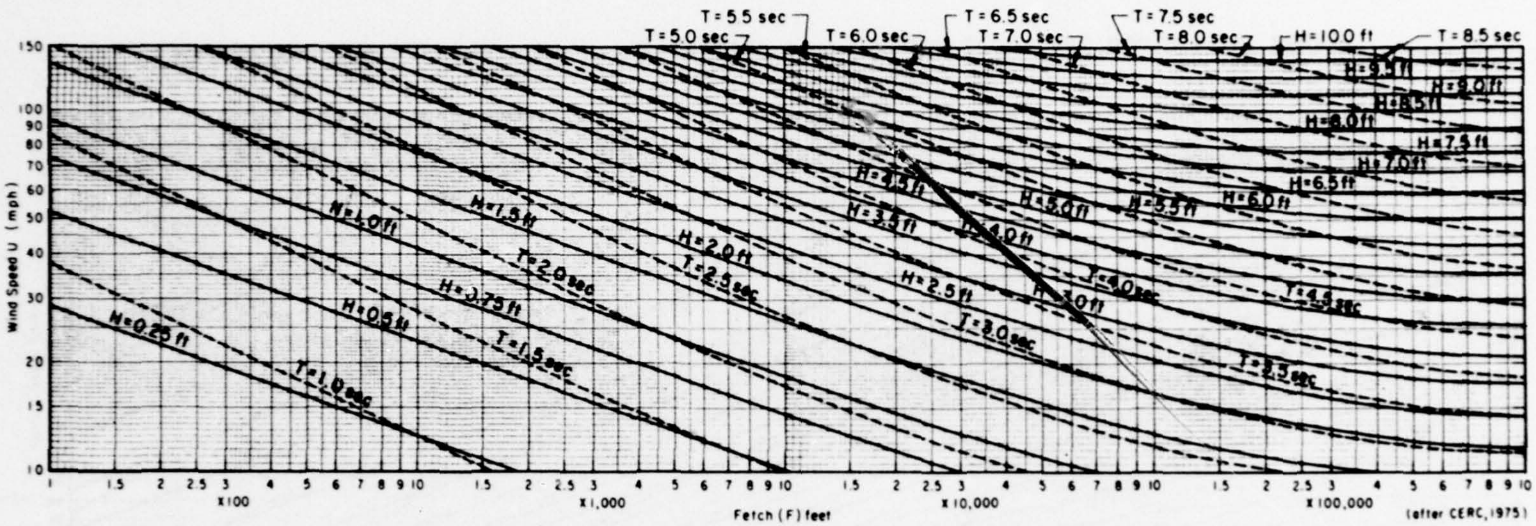

Figure 7. Forecasting curves for shallow-water waves (constant depth = 25 feet).

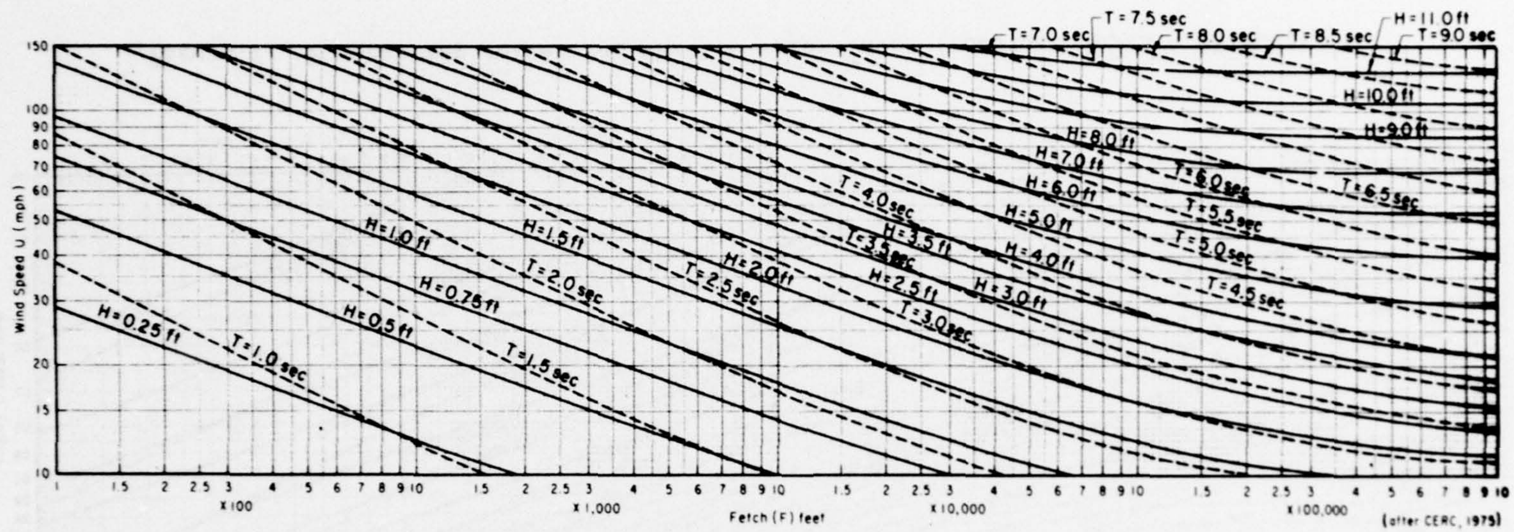

Figure 8. Forecasting curves for shallow-water waves (constant depth = 30 feet).

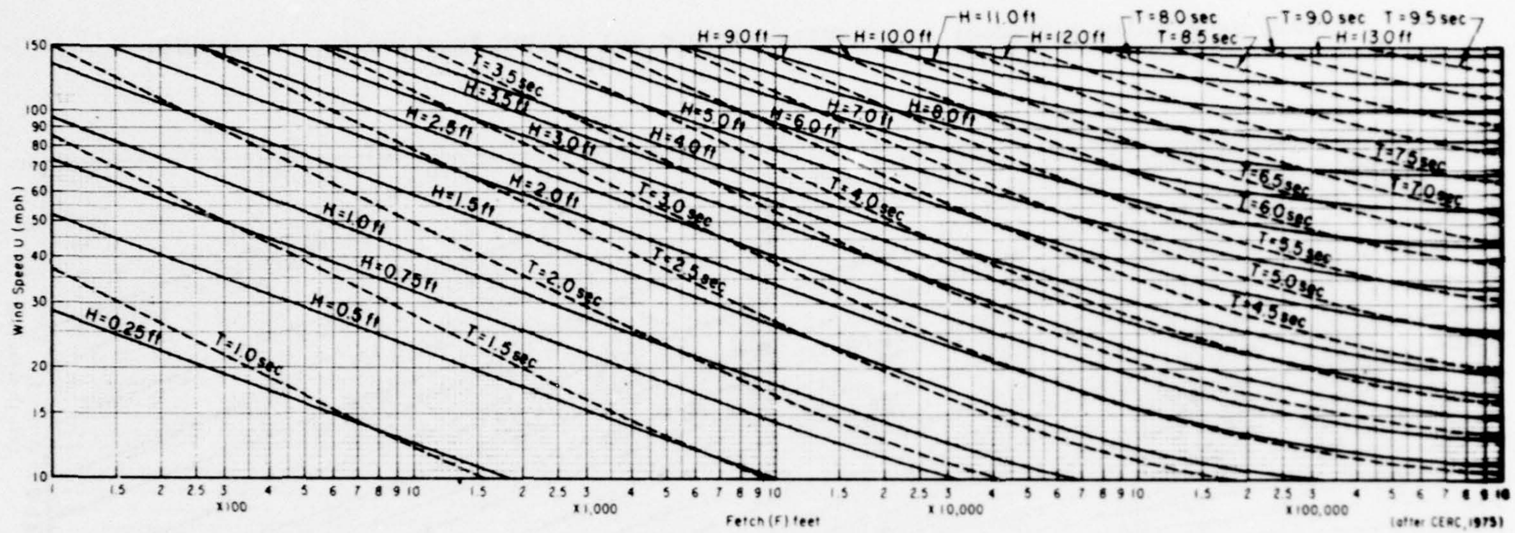

Figure 9. Forecasting curves for shallow-water waves (constant depth = 35 feet).

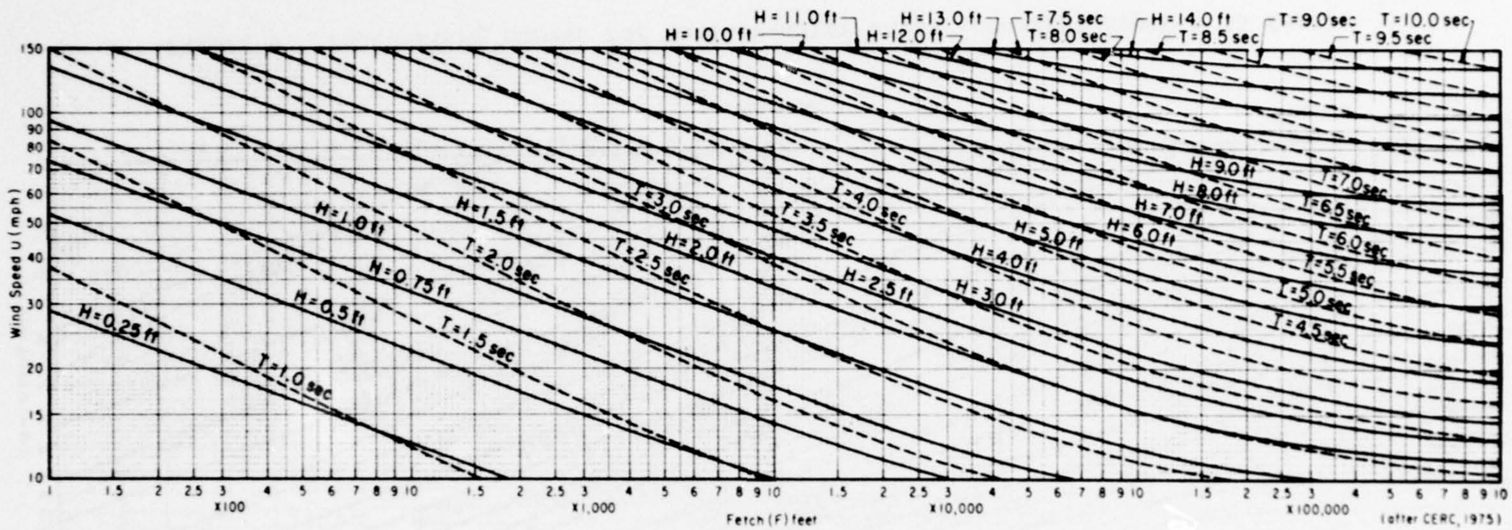

Figure 10. Forecasting curves for shallow-water waves (constant depth = 40 feet).

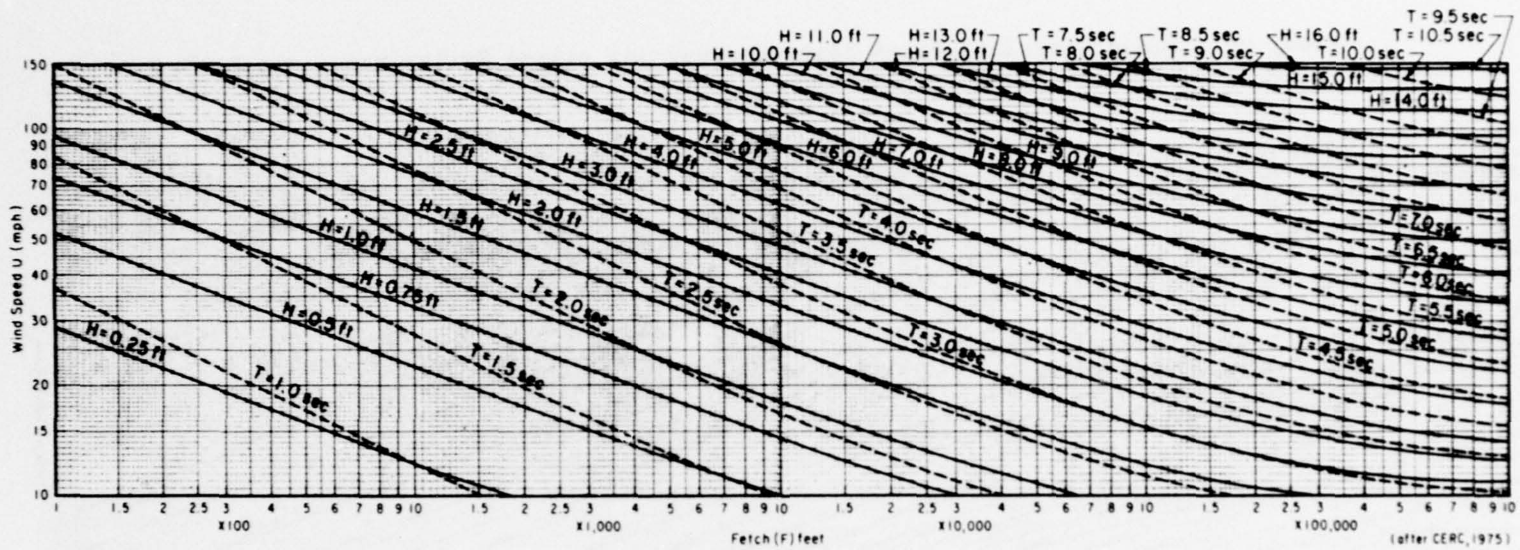

Figure 11. Forecasting curves for shallow-water waves (constant depth = 45 feet).

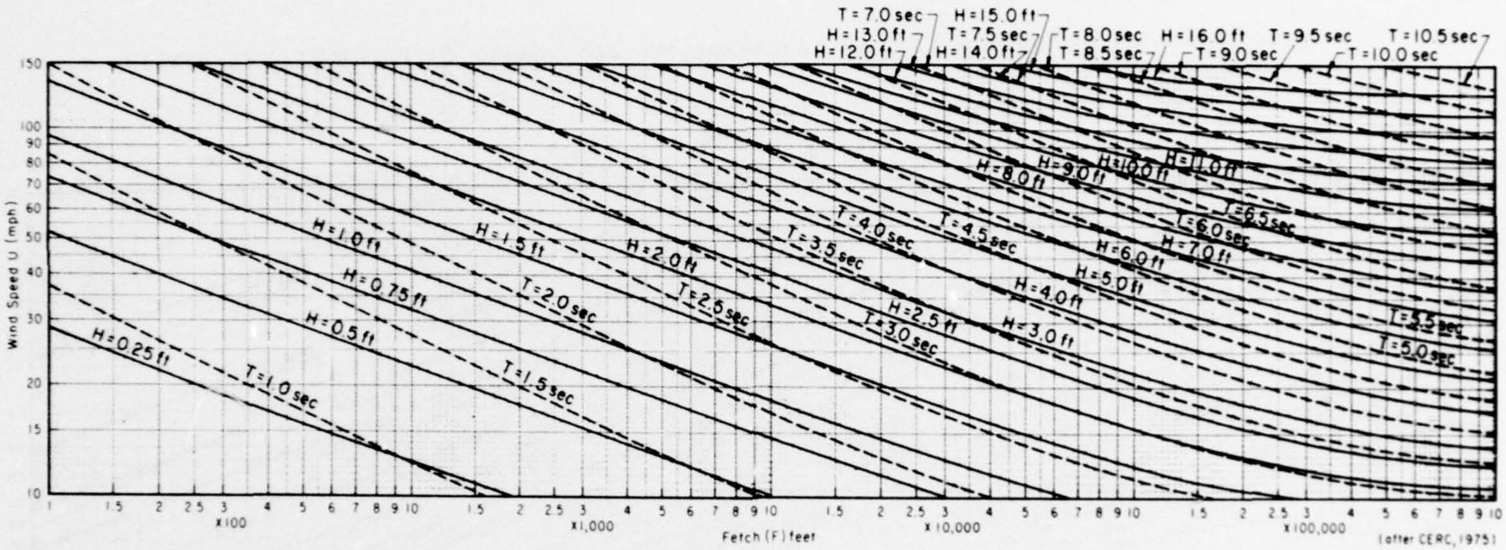

Figure 12. Forecasting curves for shallow-water waves (constant depth = 50 feet).

The bottom friction, f_f, can be obtained from Figure 13 for a known type of vegetation. The adjusted fetch distance, F_a, for a segment distance, Δx, is then obtained using values of the decay factor, K_f, from Figure 14 (after Bretschneider, 1954)[3]. An adjustment factor α, where $H_i < H_{sm}$, is defined as

$$\alpha = \frac{1 - K_{f.01}}{1 - K_{fa}} \tag{4}$$

where $K_{f.01}$ is the decay factor for a bottom-friction factor, $f_f = 0.01$, and K_{fa} is the decay factor for the actual bottom-friction factor. The adjusted fetch length, F_a, is then given as

$$F_a = \alpha \, \Delta x \ . \tag{5}$$

An adjustment factor, α_r, where $H_i > H_{sm}$, is defined as

$$\alpha_r = \frac{1 - K_{fa}}{1 - K_{f.01}} \tag{6}$$

and, for a decaying wave,

$$F_a = \alpha_r \, \Delta x \ . \tag{7}$$

III. WAVE GROWTH

For any given water depth, windspeed, and fetch length, a maximum significant wave height, H_{sm}, which would be generated can be defined from Figure 1. If the initial wave height, H_i, at the seaward or beginning edge of the fetch segment is less than H_{sm}, it is assumed that the wave will increase in height.

To find the wave growth, first determine an equivalent fetch length, F_e, for the initial wave (obtained directly from Fig. 1 using the given windspeed and water depth). Secondly, the adjusted fetch, F_a, is determined using equations (4) and (5) and Figure 14. The total fetch is then given as

$$F = F_e + F_a \ . \tag{8}$$

Re-entering Figures 1 and 2 with the fetch length, F, and the windspeed, U, and water depth, d, the wave height and period at the end of the fetch segment, H_f and T, are determined.

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[3]BRETSCHNEIDER, C.L., "Modification of Wave Height Due to Bottom Friction, Percolation, and Refraction," TM-45, U.S. Army, Corps of Engineers, Beach Erosion Board, Washington, D.C., Oct. 1954.

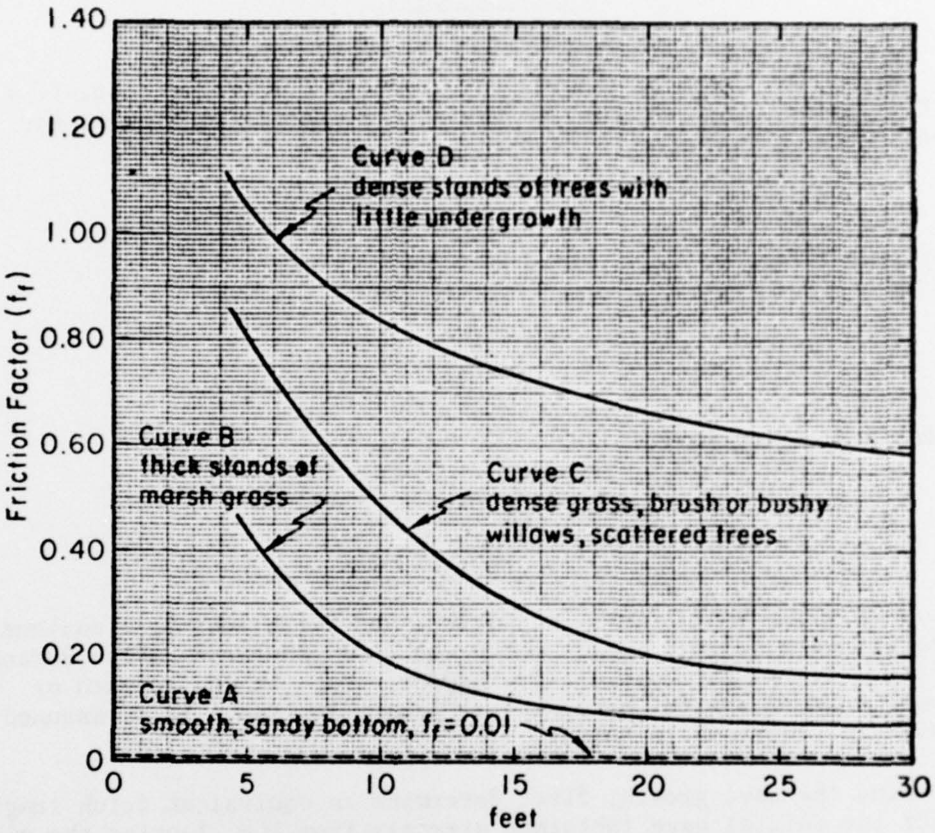

Figure 13. Bottom-friction factors.

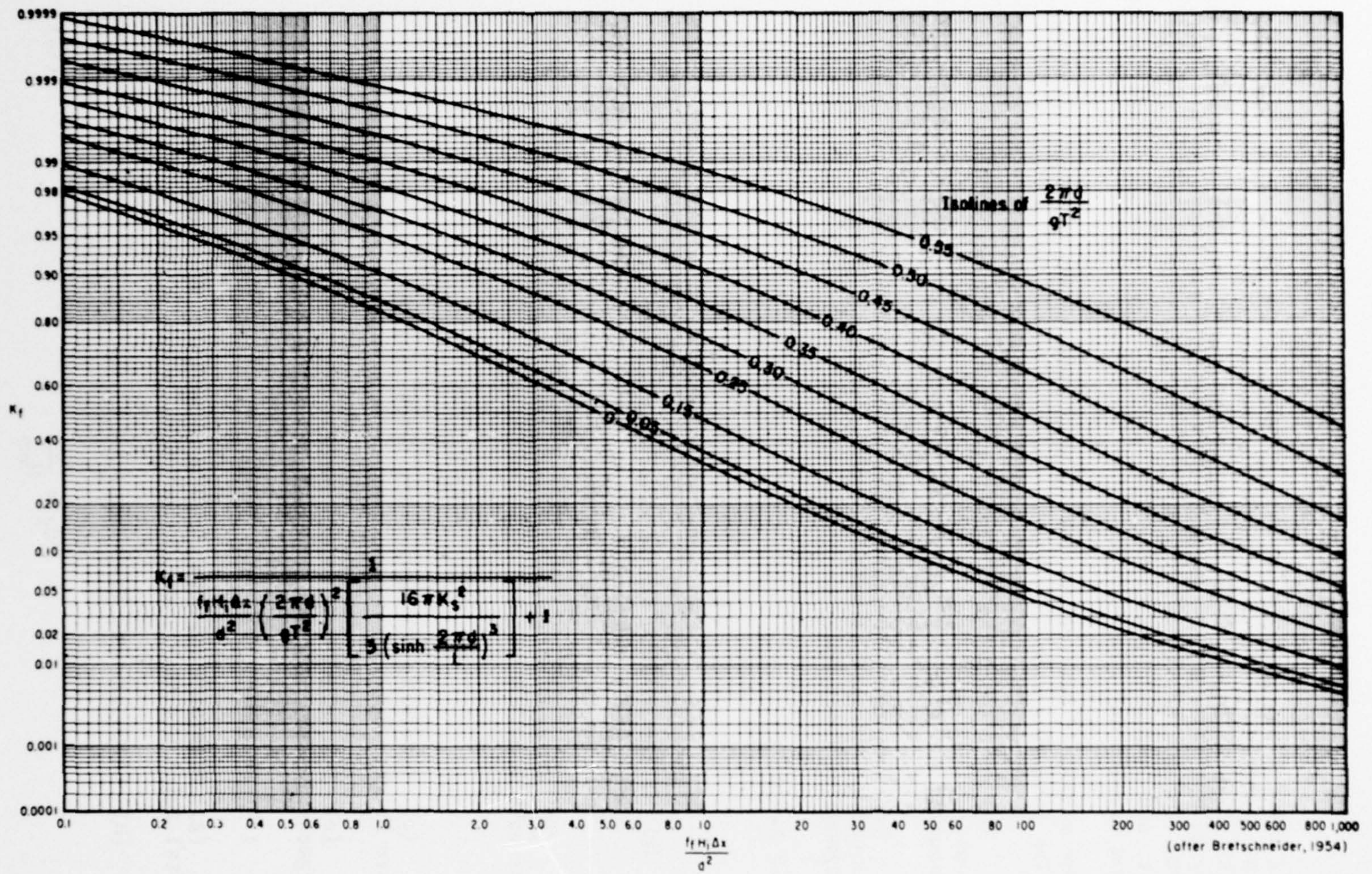

Figure 14. Decay factors.

IV. WAVE DECAY

If the initial significant wave height, at the seaward or beginning edge of a segment of fetch, exceeds the maximum significant wave height for the given water depth of the segment of fetch and the given windspeed, it may be assumed that the effects of the bottom friction will exceed the effects of the wind stress. Therefore, the wave will decay, will lose height, and over a long distance will approach a wave height equal to the maximum significant wave height.

The method of determining the decayed wave height is shown in Figure 15. The following steps are used to predict the decay of a wave:

(a) Determine the maximum significant wave height that would be generated for a given windspeed and water depth, assuming an unlimited fetch and using Figure 1.

(b) Determine the fractional reduction, R_i, represented by the initial wave at the seaward edge of the segment of fetch under consideration.

This is given by

$$R_i = \frac{H_m - H_i}{H_m - H_{sm}} \tag{9}$$

where H_m is the maximum stable wave height given as

$$H_m = 0.78\ d\ . \tag{10}$$

(c) Determine the equivalent initial wave height, H_{ie}, for wave growth by

$$H_{ie} = R_i\ H_{sm}\ . \tag{11}$$

(d) Determine the equivalent fetch length, F_e, for the wave height, H_{ie}.

(e) Determine an adjusted fetch length, F_a, for the segment length, Δx, using equations (6) and (7).

(f) Determine the total fetch, F, from equation (8).

(g) Determine an equivalent wave height, H_e, for the total fetch and the given windspeed and water depth.

(h) Calculate the fractional growth by

$$G_i = \frac{H_e}{H_{sm}}\ . \tag{12}$$

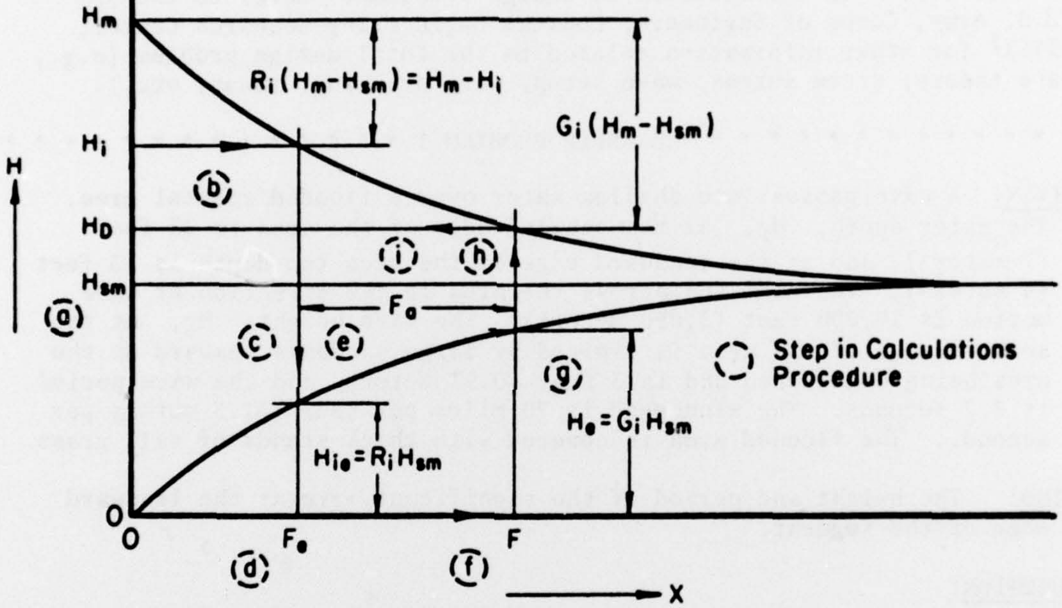

Figure 15. Schematic of wave decay calculations.

(i) Calculate the decayed wave height at the end of the fetch by

$$H_D = H_m - G_i\ (H_m - H_{sm})\ . \tag{13}$$

As a conservative estimate, it is assumed that the wave period remains constant as the wave decays.

V. SAMPLE DESIGN PROBLEMS

The following examples demonstrate the use of the techniques discussed in this report in the sclution of design problems. Refer to the SPM (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1975)[1] for other information related to the total design problem (e.g., wave theory, storm surges, wave setup, wave breaking, runup, etc.).

* * * * * * * * * * * * * * * EXAMPLE PROBLEM 1 * * * * * * * * * * * * * * *

GIVEN: A wave passes into shallow water over a flooded coastal area. The water depth, d_i, at the seaward edge of the area is 23 feet (7 meters), and at the landward edge of the area the depth is 13 feet (4 meters). The distance across the area in the direction of wave motion is 10,000 feet (3,050 meters). The wave height, H_i, at the seaward edge of the area is limited by large sandbars seaward of the area being considered and is 3 feet (0.91 meter), and the wave period is 3.2 seconds. The windspeed is 70 miles per hour (31.3 meters per second). The flooded area is covered with thick stands of tall grass.

FIND: The height and period of the significant wave at the landward edge of the segment.

SOLUTION:

$$0.25\ d_i = 0.25\ (23) = 5.75 \text{ feet}$$

$$\Delta d = 23 - 13 = 10 \text{ feet} > 0.25\ d_i\ .$$

Since this does not meet the condition of equation (1), the area should be divided into two fetch segments. Assuming a uniform variation in depth, take the first segment as a distance Δx = 5,000 feet with a depth variation from 23 to 18 feet. Then

$$\Delta d = 23 - 18 = 5 \text{ feet} < 0.25\ d_i\ .$$

At the 23-foot depth (from Fig. 13, curve B),

$$f_f = 0.080$$

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[1]U.S. ARMY, CORPS OF ENGINEERS, COASTAL ENGINEERING RESEARCH CENTER, op. cit., p. 9.

and at the 18-foot depth (curve B),

$$f_f = 0.095$$

$$\Delta f_f = 0.095 - 0.080 = 0.015$$

$$0.25\ f_{fi} = 0.25\ (0.080) = 0.020$$

$$\Delta f_f < 0.25\ f_{fi}\ .$$

Equations (4) and (5) are satisfied, so the fetch segment chosen is used. For a uniformly varying depth, the average depth can be taken as the average of the depths at the beginning and the end of the segment; i.e.,

$$d = \frac{23 + 18}{2} = 20.5 \text{ feet}\ .$$

For a uniform type of vegetation, the friction factor will vary as a function of water depth (see Fig. 13). As an approximation, the average friction factor can be taken as the average of the friction factors at the beginning and the end of the segment; i.e.,

$$f_f = \frac{0.080 + 0.095}{2} = 0.088\ .$$

For d = 20.5 feet, H = 3 feet, and U = 70 miles per hour (102.7 feet per second),

$$\frac{gd}{U^2} = \frac{32.2 \times 20.5}{(102.7)^2} = 0.0626$$

$$\frac{gH_i}{U^2} = \frac{32.2 \times 3}{(102.7)^2} = 0.00916$$

and from Figure 1

$$\frac{gF}{U^2} = 12.2$$

$$F = 12.2\ \frac{U^2}{g} = 12.2\ \frac{(102.7)^2}{32.2} = 4,000 \text{ feet}\ .$$

For $f_f = 0.01$,

$$\frac{f_f\ H_i\ \Delta x}{d^2} = \frac{0.01 \times 3 \times 5,000}{20.5^2} = 0.357\ ;$$

for $f_f = 0.088$,

$$\frac{f_f H_i \Delta x}{d^2} = \frac{0.088 \times 3 \times 5{,}000}{20.5^2} = 3.14 \ .$$

For the period, T = 3.2 seconds, and d = 20.5 feet,

$$\frac{2\pi d}{gT^2} = \frac{2\pi\ (20.5)}{32.2\ (3.2)^2} = 0.391 \ .$$

For $2\pi d/(gT^2) = 0.391$ (from Fig. 14)

$$K_{f.01} = 0.996 \text{ for } f_f = 0.01 \text{ and } f_f H_i \Delta x/d^2 = 0.357$$

$$K_{fa} = 0.965 \text{ for } f_f = 0.088 \text{ and } f_f H_i \Delta x/d^2 = 3.14 \ .$$

From equation (4),

$$\alpha = \frac{1 - K_{f.01}}{1 - K_{fa}} = \frac{1 - 0.996}{1 - 0.965} = \frac{0.004}{0.035} = 0.114 \ ;$$

from equation (5),

$$F_a = \alpha \Delta x = 0.114\ (5{,}000) = 570 \text{ feet} \ ;$$

from equation (8),

$$F = F_e + F_a = 4{,}000 + 570 = 4{,}570 \text{ feet} \ .$$

For d = 20.5 feet, U = 70 miles per hour, and F = 4,570 feet (from Figs. 1, 2, or 6)

$$H_f = 3.17 \text{ feet and } T = 3.31 \text{ seconds}$$

$$\Delta H = 3.17 - 3 = 0.17 \text{ foot} < 0.50\ H_i \ .$$

This satisfies the requirements of equation (3), and the solution may proceed to the next segment which is the remaining 5,000 feet of the area, with the water depth varying from 18 to 13 feet.

$$0.25\ d_i = 0.25\ (18) = 4.5 \text{ feet} \ .$$

Since $\Delta d = 18 - 13 = 5$ feet $> 0.25\ d_i$, which does not satisfy equation (1), a shorter segment is required. For a 3,000-foot segment, assuming a uniform depth variation, the depth will vary from 18 to 15 feet. For the 15-foot depth (using curve B in Fig. 13)

$$f_f = 0.120$$

$f_{fi} = 0.095$ at the 18-foot depth as previously shown.

$$\Delta f_f = 0.120 - 0.095 = 0.025 \simeq 0.25\ f_{fi} \ .$$

This satisfies equation (2) and the solution may proceed. The average depth, d = 16.5 feet, and the average friction factor, $f_f = 0.108$. For d = 16.5 feet and H_i = 3.17 feet (from Fig. 1).

$$f_e = 5{,}400 \text{ feet ;}$$

for d = 16.5 feet, H_i = 3.17 feet, f_f = 0.108, Δx = 3,000 feet, and T = 3.31 seconds (from Fig. 14),

$$\frac{2\pi d}{gT^2} = 0.294$$

$$K_{f.01} = 0.988 \text{ for } f_f = 0.01 \text{ and } f_f\, H_i\, \Delta x/d^2 = 0.349$$

$$K_{fa} = 0.88 \text{ for } f_f = 0.108 \text{ and } f_f\, H_i\, \Delta x/d^2 = 3.77 .$$

Using equation (4), α = 0.1 and

$$F_a = \alpha\, \Delta x = 0.1\ (3{,}000) = 300 \text{ feet}$$

$$F = F_e + F_a = 5{,}400 + 300 = 5{,}700 \text{ feet .}$$

For d = 16.5 feet (from Figs. 1 and 2),

$$H_f = 3.27 \text{ feet and } T = 3.41 \text{ seconds .}$$

The remaining 2,000 feet of the fetch can then be treated as a third segment. The average depth, d = 14 feet, and the average friction factor is f_f = 0.13.

For d = 14 feet and H_i = 3.27 feet (from Fig. 1),

$$F_e = 7{,}200 \text{ feet ;}$$

for d = 14 feet, H_i = 3.27 feet, f_f = 0.13 (from Fig. 13)

$$\Delta x = 2{,}000 \text{ feet, } T = 3.41 \text{ seconds, and } 2\pi d/(gT^2) = 0.235$$

$$K_{f.01} = 0.98 \text{ for } f_f = 0.01 \text{ and } f_f\, H_i\, \Delta x/d^2 = 0.334$$

$$K_{fa} = 0.80 \text{ for } f_f = 0.13 \text{ and } f_f\, H_i\, \Delta x/d^2 = 4.34 .$$

Using equation (4), α = 0.1 and

$$F_a = \alpha\, \Delta x = 0.1\ (2{,}000) = 100 \text{ feet}$$

$$F = F_e + F_a = 7{,}200 + 200 = 7{,}400 \text{ feet .}$$

For d = 14 feet, U = 70 miles per hour, and F = 7,400 feet (from Figs. 1 and 2)

$$H_f = 3.34 \text{ feet and } T = 3.51 \text{ seconds .}$$

NOTE.--For a sandy bottom, $f_f = 0.01$, the wave would have increased to a height of approximately 4.26 feet, a 42-percent increase from the initial wave height of 3 feet. For thick stands of tall grass, the predicted increase in wave height is only 11 percent using the approximate method of solution discussed in this report.

* * * * * * * * * * * * * * * * * * EXAMPLE PROBLEM 2 * * * * * * * * * * * * * * *

GIVEN: A coastal area is flooded by a storm surge so that the water depth over the area is 10 feet (3.05 meters). The actual fetch across the area, in the direction of wave travel, is 3,000 feet (914 meters). The area is covered with thick stands of tall grass and a small to moderate amount of brush or low, bushy trees in an even distribution. The windspeed is 90 miles per hour (132 feet per second or 40.2 meters per second) and the initial wave height at the seaward edge of the area is 6 feet (1.83 meters); the wave period is 4.5 seconds.

FIND: The decayed wave height at the end of the fetch.

SOLUTION: From the long dashline in Figure 1, for the windspeed of 90 miles per hour and the water depth of 10 feet,

$$\frac{gd}{U^2} = \frac{32.2 \times 10}{(132)^2} = 0.0185$$

giving (at the intersection of the above line with the long dashline)

$$\frac{gH}{U^2} = 0.0075$$

so that the maximum significant wave height

$$H_{sm} = \frac{0.0075\ U^2}{g} = \frac{0.0075\ (132)^2}{32.2} = 4.1 \text{ feet .}$$

From equation (10),

$$H_m = 0.78d = 0.78\ (10) = 7.8 \text{ feet}$$

and from equation (9), the fractional reduction is

$$R_i = \frac{H_m - H_i}{H_m - H_{sm}} = \frac{7.8 - 6}{7.8 - 4.1} = 0.486 \text{ .}$$

From equation (11), the equivalent initial wave height

$$H_{ie} = R_i\ H_{sm} = 0.486 \times 4.1 = 1.99 \text{ feet ;}$$

from Figure 1, for

$$\frac{gH}{U^2} = \frac{32.2\ (1.99)}{(132)^2} = 0.00368$$

and

$$\frac{gd}{U^2} = 0.0185\ ,$$

the fetch is given by

$$\frac{gF}{U^2} = 1.4\ .$$

F = 760 feet for the 90-mile per hour windspeed, so that the equivalent fetch

$$F_e = 760 \text{ feet}\ .$$

The vegetation does not match any of the curves in Figure 13, but falls between curves B and C. Assuming that a moderate amount of brush will give a friction effect about halfway between the two curves, from curve B, where d = 10 feet, $f_f = 0.20$, and from curve C, where d = 10 feet, $f_f = 0.485$. The bottom friction is then taken, in this case, as the average of the two values

$$f_f = \frac{0.20 + 0.485}{2} = 0.343\ .$$

For $f_f = 0.01$,

$$\frac{f_f\ H_i\ \Delta x}{d^2} = \frac{0.01 \times 6 \times 3{,}000}{10^2} = 1.8\ ;$$

for $f_f = 0.343$,

$$\frac{f_f\ H_i\ \Delta x}{d^2} = \frac{0.343 \times 6 \times 3{,}000}{10^2} = 61.7\ ;$$

for T = 4.5 seconds and d = 10 feet,

$$\frac{2\pi d}{gT^2} = \frac{2\pi\ (10)}{g\ (4.5)^2} = 0.096\ .$$

From Figure 14,

$$K_{f.01} = 0.80 \text{ for } f_f = 0.01 \text{ and } f_f\ H_i\ \Delta x/d^2 = 1.8$$

$$K_{fa} = 0.105 \text{ for } f_f = 0.343 \text{ and } f_f\ H_i\ \Delta x/d^2 = 61.7\ .$$

From equation (6),

$$\alpha_r = \frac{1 - K_{fa}}{1 - K_{f.01}} = \frac{1 - 0.105}{1 - 0.80} = \frac{0.895}{0.20} = 4.48 \ ;$$

from equation (7),

$$F_a = \alpha_r \, \Delta x = 4.48 \ (3{,}000) = 13{,}440 \text{ feet}$$

(i.e., the wave decay over 3,000 feet of tall grass with some brush is equal to the wave decay over 13,440 feet of a sand bottom for this water depth and windspeed).

The total fetch from equation (8) is

$$F = F_e + F_a = 760 + 13{,}440 = 14{,}200 \text{ feet.}$$

For a windspeed of 90 miles per hour and a fetch of 14,200 feet (from Fig. 1)

$$\frac{gd}{U^2} = 0.0185 \text{ (as previously determined)}$$

$$\frac{gF}{U^2} = \frac{32.2 \times 14{,}200}{(132)^2} = 26.24$$

giving

$$\frac{gH}{U^2} = 0.0071 \ .$$

From which the equivalent wave height,

$$H_e = \frac{0.0071 \ U^2}{g} = \frac{0.0071 \ (132)^2}{32.2} = 3.84 \text{ feet .}$$

From equation (12), the fractional growth is

$$G_i = \frac{H_e}{H_{sm}} = \frac{3.84}{4.1} = 0.937 \ .$$

The decayed wave height is then given by equation (13) as

$$H_D = H_m - G_i \ (H_m - H_{sm}) = 7.8 - 0.937 \ (7.8 - 4.1) = 4.33 \text{ feet .}$$

At the end of the fetch segment, the wave height and period are approximated by

$$H_D = 4.33 \text{ feet}$$

$$T = 4.5 \text{ seconds .}$$

* *

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